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Tightly Focusing Properties of Radially Polarized Double Ring Shaped Beam through a Uniaxial Birefringent Crystal

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Abstract

The properties of radially polarized Double ring shaped beam tightly focused through a uniaxial birefringent crystal are studied numerically by the use vectorial diffraction theory for small birefringence. The intensity distribution of focal structure in the focal region can be shift along the longitudinal axis with increasing the birefringence value [Δn], and splitting of focal spot can be obtained by changing the pupil to beam ratio[β].and also splitting of single focal spot into double spot by changing the pupil to beam ratio[β] .

Keywords:

1. INTRODUCTION

Tight focusing of laser beam has attracted much attention because of its much smaller focus spot and strong longitudinal component (Urbach and Pereira, 2008; Dorn *et al.* 2003; Yan *et al.* 2011). Tightly focused light beams can increase the imaging resolution and enhance the localized electric field at the nanometer scale in a variety of microscopes and spectroscopes. Tightly focused light beams have wide potential applications in optical data storage, optical trapping, and microscopy (Zhang *et al.* 2008; Youngworth and Brown, 2000; Lerman and Levy, 2007; Walker and Milster, 2001; Helseth, 2001). The longitudinal field component at the focal point of a radially polarized beam (RPB) is larger than that of any other focused field (Urbach and Pereira, 2008). In 2003, direct detection and characterization of this sharp longitudinal field by experimental demonstration was reported (Dorn *et al.* 2003). Tightly focused radially polarized beam has many attractive applications such as particle acceleration (Romea and Kimura, 1990), fluorescent (Novotny *et al.* 2003), second harmonic generation (Yew and Sheppard, 2007), Raman spectroscopy (Hayazawa *et al.* 2004), optical trapping (Zhan, 2004) material processing (Niziev and Nesterov, 1999) and particle acceleration (Tidwell *et al.* 1993), optical data storage (Xiangping *et al.* 2007), applications in high-resolution microscopy (Cheng *et al.* 2011), surface plasmon excitation (Zhan, 2006), particles accelerating (Varin and Piche, 2002) **and in** material processing (Meier *et al.* 2007). Normally the focusing beam was assumed to be single-ring-shaped beam, which is often referred to as a radially polarized TEM01* (R-TEM01 *) mode beam (Dorn *et al.* 2003; Youngworth and Brown, 2000; Quabis *et al.* 2000). On the other hand, a double-ring-shaped beam was experimentally observed as a higher-order radially polarized mode (R-TEM11*) directly from a laser cavity (Moser *et al.* 2005). Double-ring-shaped radially polarized mode(R-TEM11*) beams can effectively reduce the spot size by destructive interference between the inner and the outer rings with pi phase shift (Kozawa and Sato, 2006; 2007). Recently modulating the focal patterns using double ring shaped beam is a topic of great interest and many works are reported (Nie *et al.* 2014; Rajesh *et al.* 2011; Tian and Pu, 2014; Lalithambigai *et al.* 2013; Zhang *et al.* 2009; 2010). Many optical components, including wave plates, compensators, polarizer, and so on, make use of the birefringent effect of uniaxial crystals to realize their own functions. Thus, it is of practical significance to study the propagation dynamics of light beams in uniaxial crystals. The properties of light beams propagating in birefringent materials have attracted many researchers' interest for years (Fleck and Feit,

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1983; Stallinga, 2001; Ciattoni *et al.* 2002; Avendano-Alejo and Rosete-Aguilar, 2006). Ciattoni etal have been studying the propagation of a paraxial optical beam along the optical axis of a uniaxial crystal in a series of papers (Ciattoni *et al.* 2002; 2003; 2001a; 2001b; 2001c; 2002a; 2002b; 2002c; 2002d; Provenziani *et al.* 2002; Ciattoni *et al.* 2002; 2003). Stamnes etal presented consistent numerical and experimental results for the focusing of two/three dimensional electromagnetic waves into uniaxial crystal (Jain *et al.* 2009; Stamnes and Jiang, 1998; Jiang and Stamnes, 2000). The propagation of various kinds of laser beams in uniaxial crystals parallel and orthogonal to the optical axis has been reported (Lu and Luo, 2004; Deng *et al.* 2008; Tang, 2009; Li *et al.* 2010; 2011; Zhou *et al.* 2012; Deng *et al.* 2007; Liu and Zhou, 2008; 2009a; 2009b; 2009c; Du and Zhao, 2010; Zhang and Cai, 2011; Li and Chen, 2012; Zhou *et al.* 2013; Deng *et al.* 2013; Shen *et al.* 2014; Zhang and Cai, 2011). The tight focusing of radially, azimuthally and circularly polarized laser beams through a uniaxial crystal associated with focal shift have received a lot of attention because of the theoretical and experimental interest (Zhang *et al.* 2008; Yonezawa *et al.* 2008; Rao and Wang, 2008). In this paper, based on the theoretical model of Ref. (Zhang *et al.* 2008; Rao and Wang, 2008), we extend the analysis of tight focusing properties of radially polarized double ring shaped beams through a uniaxial birefringent crystal. It is shown that the intensity distribution of focal structure in the focal region can be shift along the longitudinal axis with increasing the birefringence value [Δn], and splitting of focal spot can be obtained by changing the pupil to beam ratio[β].

Fig.1. shows the schematic diagram of the focusing system. Here the radially polarized double ring shaped beams is assumed to focus from medium 1 into medium 2 (see Fig. 1). Medium 1 is isotropic where as medium 2 is a uniaxial birefringent with its uniaxial symmetrical axis along optical axis. Here *d* is the probe depth which is the distance between the interface and geometrical focus (Torok *et al.* 1995). $\hat{k}_1$ and $\hat{k}_2$ are the wave vectors in medium 1 and medium 2 with $\hat{s}_1\ \hat{p}_1$ and $\hat{s}_2\ \hat{p}_2$ are the corresponding polarization vectors in parallel and perpendicular direction to the plane of incidence. Based on vectorial Debye theory (Gu, 2000), Cartesian components of the electric field vector in the focal region can be expressed as

$$E_{tot} = E_x(r,\psi,z) + E_y(r,\psi,z) + E_z(r,\psi,z) \rightarrow 1$$

Where

$$E_x(r,\psi,z) = \frac{-iE_o}{\pi}\int_0^{\alpha}\int_0^{2\pi} \sin\theta_1\sqrt{\cos\theta_1}P(\theta_1)$$

$$\exp[ik_2 z\cos\theta_2 + ik_1 r\sin\theta_1\cos(\psi-\phi)]$$

$$[t_p\cos\theta_2\cos\phi\exp[ik_o(W+\Delta W)]]\exp(-i\phi)d\phi d\theta_1 \rightarrow 2$$

$$E_y(r,\psi,z) = \frac{-iE_o}{\pi}\int_0^{\alpha}\int_0^{2\pi} \sin\theta_1\sqrt{\cos\theta_1}P(\theta_1)$$

$$\exp[ik_2 z\cos\theta_2 + ik_1 r\sin\theta_1\cos(\psi-\phi)]$$

$$[t_p\cos\theta_2\sin\phi\exp[ik_o(W+\Delta W)]]\exp(-i\phi)d\phi d\theta_1 \rightarrow 3$$

and

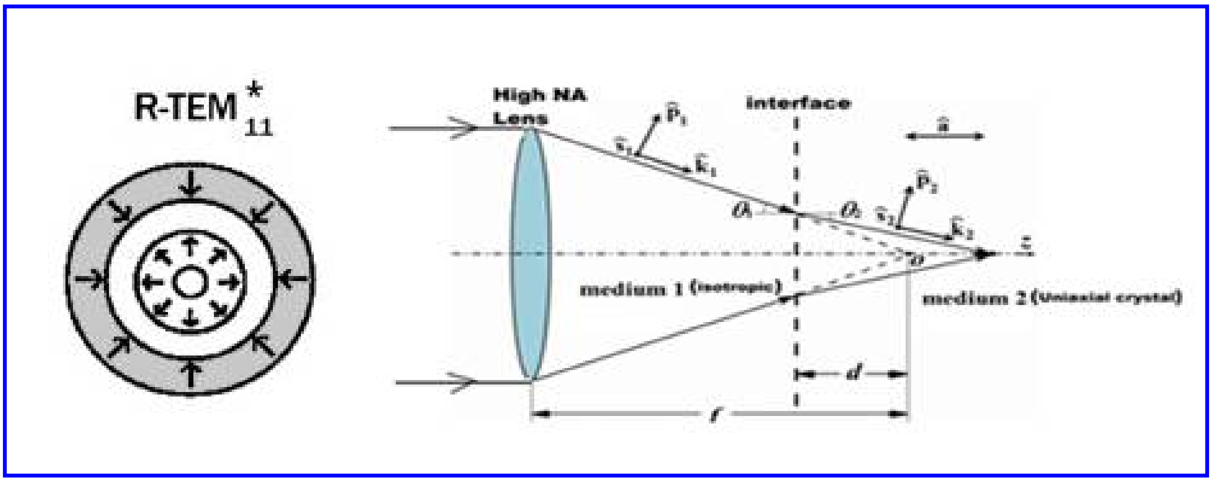

Fig. 1: Scheme of the optical system

$$E_z(r,\psi,z) = \frac{-iE_o}{\pi}\int_0^{\alpha}\int_0^{2\pi} \sin\theta_1\sqrt{\cos\theta_1}\,P(\theta_1)$$

$$\exp[ik_2 z\cos\theta_2 + ik_1 r\sin\theta_1\cos(\psi-\phi)]$$

$$[-t_p\sin\theta_2\exp[ik_o(W+\Delta W)]]\exp(-i\phi)d\phi d\theta_1 \rightarrow 4$$

Here E_o is a constant related to the focal length and the wavelength, $\alpha = \sin^{-1}(NA)$ is the maximal angle determined by the NA of the objective; t_p is the amplitude transmission coefficient for parallel polarization state which is given by the Fresnel equations (Born and Wolf, 1999)

$$t_p = \frac{2\sin\theta_2\cos\theta_1}{\sin(\theta_1+\theta_2)\cos(\theta_1-\theta_2)} \rightarrow 5$$

$W_p = W + \Delta W$ and $W_s = W$ are the aberration functions of p- and s-polarizations respectively. Here W is the aberration function caused by the mismatch of the refractive indices medium 1 and medium 2, where ΔW is the phase difference between the ordinary and extraordinary modes in the uniaxial birefringent medium 2. W and ΔW are expressed as (Stallinga, 2001).

$$W = kd(n_2\cos\theta_2 - n_1\cos\theta_1) \rightarrow 6$$

$$\Delta W = k(d+z)\Delta n\sin^2\theta_2 / \cos\theta_2 \rightarrow 7$$

Where $k = 2\pi/\lambda$ is the wave number in vacuum and d is the distance between the interface and the geometric focus ;Where $\Delta n = n_e - n_0$ represents the difference between the refractive indices of ordinary and extraordinary modes in the medium 2 which is the so-called birefringence (the ordinary and extraordinary refractive indices are n_0 and, n_e respectively, and $n_0 = n_2$). It is assumed that the focusing lens is corrected for aberrations introduced by anisotropic cover layer of thickness d and refractive index $n_2 = n_0$. As a result, $W_s = W = 0, W_p = \Delta W$.

Here is the pupil function of the incident double ring shaped LG (1, 1) beam and is given by (Kozawa and Sato, 2006)

$$P(\theta_1) = \frac{\beta_O^2\sin(\theta)}{\sin^2\alpha}\exp\left(-\frac{\beta_O^2\sin^2(\theta)}{\sin^2\alpha}\right)L_p^1\left(2\frac{\beta_O^2\sin^2(\theta)}{\sin^2\alpha}\right) \rightarrow 8$$

Where β, is the ratio of the pupil radius to the incident beam radius in front of the focusing lens and L_p^1 is the generalized Laguerre polynomial. Note that β should be greater than 1 because the outer ring of the R-TEM11* beam will be completely truncated by the pupil if $\beta \leq 1$.The focal properties are evaluated numerically for the incident radially polarized double ring shaped beam by solving the above equations using the parameters NA = 0.85, n_1 = 1, n_2 = 1.5, λ = 400 nm, d = 100 μm.

2. RESULT & DISCUSSION

Fig. 2(a-d) shows the intensity distribution in the x-z plane for the incident double ring shaped beam with β =1.1 and for different axial birefringent value (Δn). Fig. 2(e-h) shows the corresponding axial intensity distribution and Fig. 2(i-l)shows the lateral intensity distribution calculated the point of maximum axial intensity .It is observed from Fig2(a)and their corresponding radial and axial intensity distribution that the generated focal segment for $\beta = 1.1$ and $\Delta n = 0$ is a focal spot having FWHM of 0.79 λ and focal depth of 4.48 λ. However we observed that increasing the axial birefringence to Δn to 5,10,and 10^{-3} shifts the focal segment in the axial direction and the corresponding on axial maximum is found to located at z=1.8 λ,3.7 λ,5.5 λ respectively. We also noted that increasing the axial birefringence does not change the focal structure but generates only the axial shifting in the positive z axis.

Table 1. Showing the FWHM, depth of focus and focal shift for different Δn and for β=1.1

Beam Parameter $\beta = 1.1$			
Birefringence $\Delta n(10^{-3})$	**Spot size** (λ)	**Depth of Focusing** (λ)	**Position of Maximum Intensity Shifted** (λ)
0	0.79	4.48	0
5	0.79	4.48	1.8
10	0.79	4.48	3.7
15	0.79	4.48	5.5

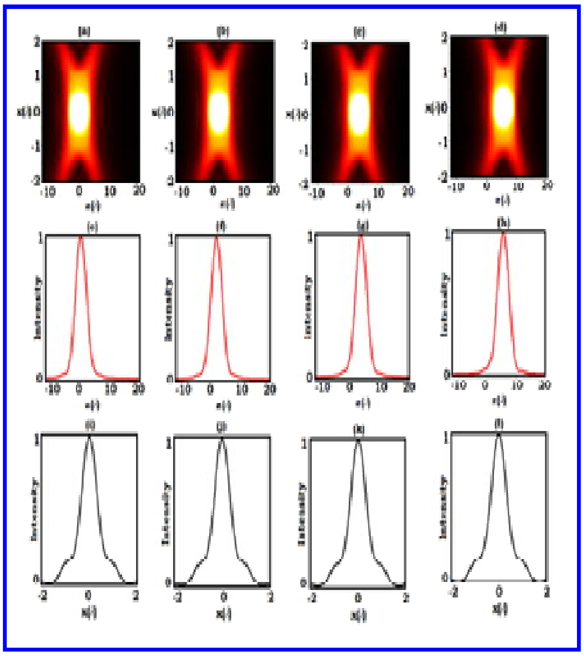

Fig. 2(a-d): 3D Intensity distribution in the x-z plane corresponding to β =1.1 and for Δn=0,5,10,15.
Fig. 2(e-h): are the corresponding axial intensity distribution.
Fig. 2(i-l): are the intensity distribution in the transverse direction measured at the point of maximum axial intensity.

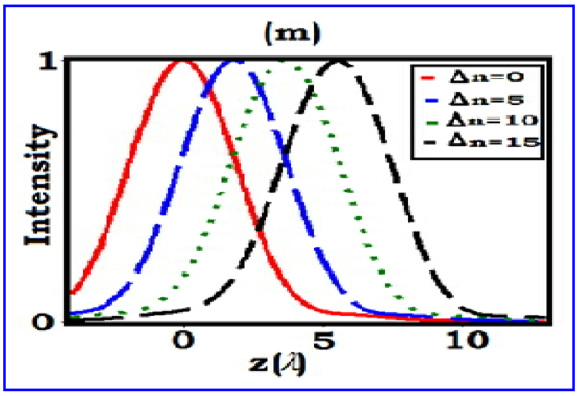

Fig. 3(m): shows focal shift in the 2D on axial intensity distribution corresponding to different Δn values.

Table 1. shows the FWHM, depth of focus and the position of maximum on axial intensity obtained for different values of axial birefringence. To produce focal shift profile one may insert a physical mask such as cosine wave plate in the pupil plane of the objective (Prabakaran *et al.* 2013; Li *et al.* 2010; Gao *et al.* 2016; 2009; Yun *et al.* 2010; Yan *et al.* 2011). However, the presence of a cosine wave plate or phase filter makes some applications more difficult or even impossible. To avoid these drawbacks here we suggest a simple method of modulating the axial birefringence to the incident radially polarized double ring shaped beam.

Fig. (3) shows the same as Fig. (2) but for β =1.5.It is noted from Fig. 3(a) and their corresponding axial and transverse intensity distribution that in the absence of axial birefringence. Increasing β to 1.5 generates an axially splitted focal segment each having FWHM of 0.74 λ and focal depth of 2.80 λ. We observed that these spots are axially separated by a distance of (5.4)λ.

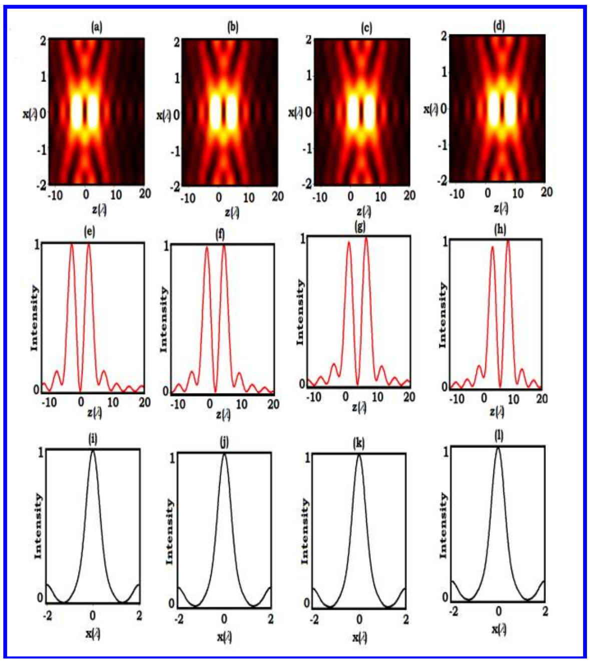

Fig. 3(a-d): 3D Intensity distribution in the x-z plane corresponding to β =1.5 and for Δn=0,5,10,15.
Fig. 3(e-h): are the corresponding 2D intensity measured in the axial direction.
Fig. 3(i-l): are the 2D intensity distribution in the transverse direction.

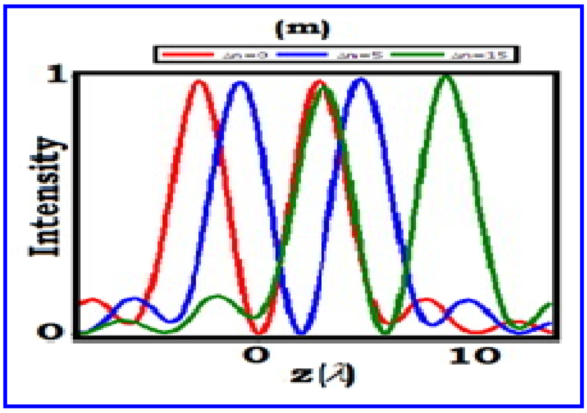

Fig. 3(m): shows focal shift in the 2D on axial intensity distribution corresponding to different Δn values.

Table 2. Showing the FWHM, depth of focus and focal shift for different Δn and for β=1.5

Beam Parameter $\beta = 1.5$			
Birefringence $\Delta n(10^{-3})$	**FWHM** (λ)	**DOF** (λ)	**Focal Shift** (λ)
0	0.74	2.80	2.70
5	0.74	2.80	4.50
10	0.74	2.80	6.40
15	0.74	2.80	8.30

It is observed from Fig. 3(b-d) and their corresponding transverse and axial intensity distribution plots ,that increasing axial birefringence shifts the generated focal segment in the positive axial direction without modulating the focal structure. Such a focal structure is useful in trapping and shifting of two indugutial particles (Gao *et al.* 2009; Qiufang Zhan *et al.* 2009). Hence it is noted that by properly manipulating the axial birefringence and pupil to beam ratio of double ring shaped beam one can generate single and axially splitted focal spots and can shift axially.

3. CONCLUSION

In conclusion, the properties of radially polarized Double ring shaped beam tightly focused through a uniaxial birefringent crystal are studied by the use vectorial diffraction theory for small birefringence. The intensity distribution of focal structure in the focal region can be shift along the longitudinal axis with increasing the birefringence value [Δn] and splitting of focal spot can be obtained by changing the pupil to beam ratio[β].and also splitting of single focal spot into double spot by changing the pupil to beam ratio [β].

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